# Effect of poloidal density variation of neutral atoms on the tokamak edge

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Neutral atoms in the tokamak edge can significantly influence global confinement by affecting the transition from low (L) to high (H) confinement. The neutrals affect the ion dynamics through charge exchange (CX), and the neutral flux of toroidal angular momentum can modify or even determine the edge radial electric field and the plasma rotation. The localization of the neutrals introduces a shear in the flow that may also affect edge turbulence. Our results suggest an external means for controlling toroidal flow and radial electric field at the edge that is being investigated on MAST [1].

Earlier theoretical work [2-4] explored the effect of neutrals on collisional ion flow and radial electric field within neoclassical theory, and found that the effect is typically significant if the fraction of atoms in the plasma exceeds about $10^{-4}$. This fraction is usually exceeded in the tokamak edge region, just inside the separatrix. In these works the effect of the poloidal variation of the neutral source was not explored. However, recent experimental observations on MAST and COMPASS-D indicate easier H-mode access when gas is puffed from the inboard side of the tokamak [1,5,6]. These experimental results show that the poloidal neutral distribution has an essential influence on the L-H transition threshold power. This observation motivates the present paper, where we use earlier results [2,4] to investigate the effect of a poloidally varying neutral source on the electric field and flow velocity of a collisional edge plasma.

The present work finds that the plasma rotation and the radial electric field depend sensitively on the poloidal location of the atoms, especially in a spherical tokamak. It is found that the radial electric field and toroidal flow velocity in a collisional edge plasma tend to be larger if the atoms are concentrated on the inboard side rather than on the outboard side. In a steady state plasma without momentum sources, there can be no radial transport of toroidal angular momentum, which implies [2] $\langle R\hat{\boldsymbol{\varphi}} \cdot (\boldsymbol{\pi}_i + \boldsymbol{\pi}_n) \cdot \nabla\psi \rangle = 0$, where $\boldsymbol{\pi}_i$ and $\boldsymbol{\pi}_n$ are the viscosity tensors of ions and neutral atoms, respectively, $\psi$ is the poloidal flux function, $R$ is the major radius and $\varphi$ is the toroidal angle. At the edge, the neutral viscosity dominates over its purely neoclassical counterpart, $\langle R\hat{\boldsymbol{\varphi}} \cdot \boldsymbol{\pi}_i \cdot \nabla\psi \rangle \ll \langle R\hat{\boldsymbol{\varphi}} \cdot \boldsymbol{\pi}_n \cdot \nabla\psi \rangle$, if $1 \lesssim (n_n v_T \lambda_x)/(n_i q^2 \rho_i^2/\tau_i) \sim (n_n/n_i)10^4$, where $\tau_i$ is the ion-ion collision time, $\lambda_x$ is the charge-exchange mean-free path, $q$ is the safety factor, $\rho_i$ is the ion gyroradius, $v_T = (2T/M)^{1/2}$ is the ion thermal velocity, and $n_n$ and $n_i$ denote the density of neutral atoms and ions, respectively. For MAST typically,

$T_i = 100$ eV, $B = 0.5$ T and $n_i = 10^{13}$ cm$^{-3}$. If $n_n/n_i > 10^{-4}$, then the radial electric field is determined by neutral atoms rather than neoclassical processes; if it is not, then the ion contribution must be retained as in [2]. It is, of course, also possible that turbulent transport of angular momentum overwhelms both the neutral and the neoclassical viscosity, in which case the electric field is determined by turbulence rather than the processes considered here.

## Plasma rotation

The axisymmetric magnetic field of a tokamak can be written as $\mathbf{B} = I(\psi)\nabla\varphi + \nabla\varphi \times \nabla\psi$. In neoclassical theory, where the transport within flux surfaces is taken to be much larger than that across the magnetic field, the density and temperature of all species are approximately constant on flux surfaces, and it follows that the ion flow velocity within a flux surface must be of the form

$$\mathbf{V}_i = \omega(\psi)R\hat{\boldsymbol{\varphi}} + u_{i\theta}(\psi)\mathbf{B}, \tag{1}$$

where $\hat{\boldsymbol{\varphi}} = R\nabla\varphi$ is the toroidal unit vector and $\omega(\psi) = -d\Phi/d\psi - 1/(n_i e)(dp_i/d\psi)$, with $\Phi$ denoting the electrostatic potential and $p_i = n_i T$ the ion pressure. In a pure hydrogen plasma (no impurities and sufficiently few neutral atoms) $u_{i\theta}(\psi) = -(kI)/(e\langle B^2\rangle)(dT/d\psi)$, with $\langle\ldots\rangle$ denoting a flux-surface average. We confine our attention to the Pfirsch-Schlüter regime, where $k \simeq 1.8 + 0.05(\langle B^2\rangle\langle(\nabla_\parallel \ln B)^2\rangle)/(\langle(\nabla_\parallel B)^2\rangle)$.

In principle, neutral atoms can affect both $\omega(\psi)$ and $u_{i\theta}(\psi)$ in Eq. (1), but $\omega(\psi)$ is much more easily affected. This quantity is determined from the condition of no radial transport of toroidal angular momentum, which for a localized neutral source leads to the following approximate expression for the toroidal ion flow:

$$V_{i\varphi} \simeq \frac{I^2}{e\langle B^2\rangle R}\frac{dT}{d\psi}\left[k\left(\frac{R^2}{R_*^2} - 1\right) + \frac{I_n^t}{I_n^s}\left(\frac{\langle B^2\rangle R^2}{I^2} - \frac{R^2}{R_*^2}\right)\right] \equiv \frac{F_v}{e}\frac{dT}{d\psi} \tag{2}$$

where $R_*$ denotes the value of $R$ at the gas puff and $I = RB_T$. If the charge-exchange mean-free path of the neutral atoms is much shorter than the radial scale length, $I_n^t/I_n^s$ is equal to unity, while it is somewhat larger at finite mean-free path [4]. This result is illustrated in Fig. 1 where we have plotted the normalized toroidal flow velocity at the outer midplane, as given by this equation, as a function of the poloidal angle of the gas puff for typical magnetic equilibria from MAST and Alcator C-Mod. Note that the rotation speed is much larger if the puff is applied on the inboard side than elsewhere on the flux surface. For a normal temperature profile, $V_{i\varphi}$ is in the counter-current direction, since $F_V > 0$.
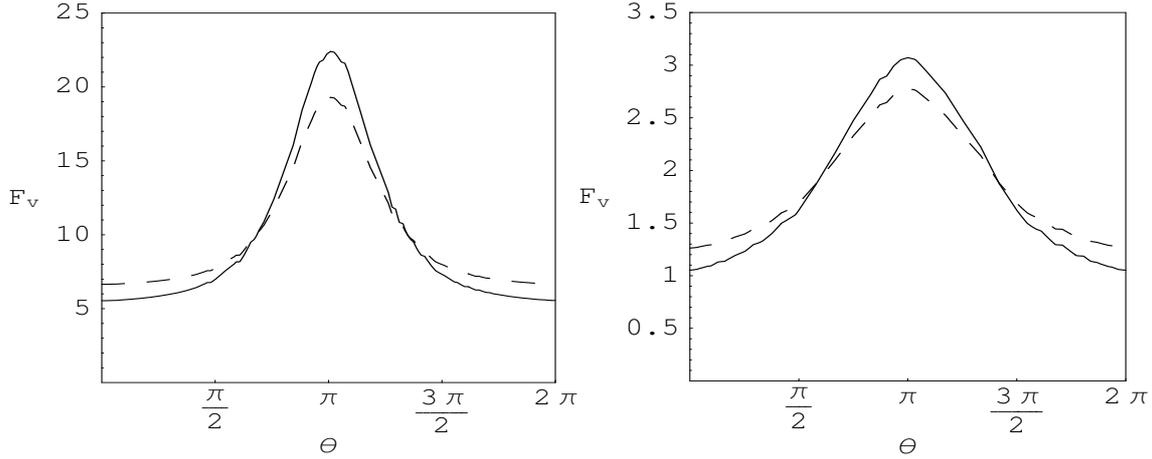
Figure 1: *Theoretically predicted toroidal flow velocity at the outer midplane of MAST(left) and Alcator C-Mod (right) as a function of the poloidal angle of the gas puff, with $\theta = \pi$ the inboard mid-plane. The solid line represents the short mean-free path limit ($I_n^t/I_n^s = 1$) and the dashed line is for $I_n^t/I_n^s = 1.2$.*

## Radial electric field

The radial electric field, $E_r$, as modified by a localized neutral source, may be evaluated from Eqs. (1) and (2), giving

$$-\frac{d\Phi}{d\psi} \simeq \frac{T}{e}\frac{d\ln n_i}{d\psi}\left\{1 + \eta_i\left[\left(k - \frac{I_n^t}{I_n^s}\right)\frac{I^2}{\langle B^2\rangle R_*^2} + \left(1 + \frac{I_n^t}{I_n^s}\right)\right]\right\} \equiv \frac{T}{e}\frac{d\ln n_i}{d\psi}F_E, \quad (3)$$

where $\eta_i = (d\ln T/d\psi)/(d\ln n_i/d\psi)$. Here, only the temperature gradient term depends on gas puff location, so that the overall sensitivity of $E_r$ to the gas puff depends on the relative size of the density and temperature gradients. Since $F_E > 0$, for a normal density profile, the radial electric field is inwards as usually observed in experiments.

Figure 2 shows that the departure of the factor $I_n^t/I_n^s$ from unity makes the effect of the neutrals weaker than in the short mean-free path case. Note that the effect of the inboard gas puffing changes the factor $F_E$ by about a factor of two when the ratio of the temperature to density gradients is $\eta_i = 2$, while the effect is lower as $\eta_i$ gets lower. Thus, the effect of neutral atoms on the radial electric field is weaker than on the ion flow, and it depends on the relative size of the density and temperature gradients.

## Discussion

In summary, the toroidal flow of the ions and the radial electric field are significantly affected by the neutrals in the edge plasma, just inside the separatrix. This effect is much larger with inboard than with outboard gas puffing, and is particularly significant at tight-aspect ratio and slightly larger at short neutral mean-free path. Moreover, the effect is independent of the neutral density provided the neutral viscosity dominates over anomalous and ion viscosities.
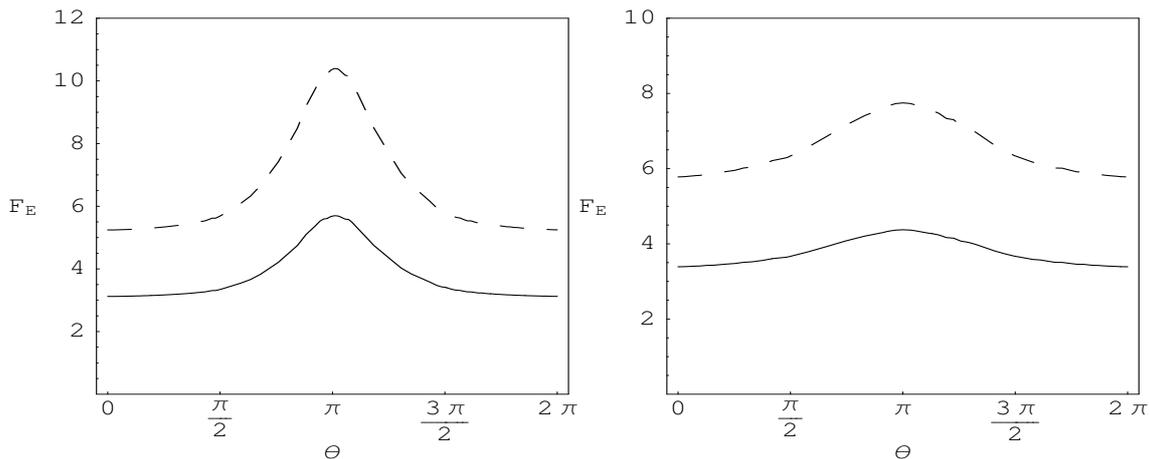
Figure 2: *Radial electric field at the outer midplane of MAST (left) and Alcator C-Mod (right) as a function of the poloidal angle of the gas puff. The solid and dashed lines represent the short mean-free path limit for $\eta_i = 1$ and $\eta_i = 2$, respectively.*

These results are interesting since they might help explain the easier access to H-mode with inboard gas puffing observed in MAST and COMPASS-D. The easier H-mode access could, for instance, be caused by suppression of edge turbulence by rotational flow shear in a narrow layer inside the separatrix, where neutral viscosity dominates. In the outboard midplane, where the turbulence is localized because of strong ballooning, the toroidal flow shear can be expected to be particularly strong if inboard gas puffing is applied according to Eq. (2). Our results suggest an external means of controlling the toroidal flow and radial electric field and their shearing rates. Very recently, experiments have been carried out on MAST to verify this theory by comparing the toroidal flow velocity with inboard and outboard gas puffing [1]. Initial results are encouraging.

[1] A. R. Field, E. R. Arends, P. G. Carolan, et al., this conference, poster P-1.114.

[2] P. Catto, P. Helander, J. W. Connor and R. D. Hazeltine, Phys. Plasmas **5**, 3961 (1998).

[3] T. Fülöp, Peter J. Catto and P. Helander, Phys. Plasmas **5**, 3398 and 3969 (1998).

[4] T. Fülöp, Peter J. Catto and P. Helander, Phys. Plasmas **8**, 5214 (2001).

[5] M. Valovic, P. G. Carolan, A. R. Field, S. J. Fielding et al., Plasma Phys. and Control. Fusion, **44**, A175 (2002).

[6] A. R. Field, P. G. Carolan, R. J. Akers, E. R. Arends et al., Plasma Phys. and Control. Fusion, **44**, A113 (2002).